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NBS TECHNICAL NOTE 575

On the Absorptance of Cavity-Type Receivers

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On the Absorptance of Cavity-Type Receivers

Jon C. Geist and Joseph C. Richmond

The directional-hemispherical reflectance of a number of flat samples that had been coated with Parsons Optical Black Lacquer procured from Thos. Parsons and Sons and The Eppley Laboratory, respectively, was measured at 0.6328 and 1.15 μm with a laser-source integrating sphere reflectometer. The reflectance varied significantly with method of application, and was significantly higher for the Eppley lacquer than for the Parsons lacquer. The reflectance of two cavity receivers, one coated with each lacquer, was also measured. At 0.6328 μm the reflectance of the Parsons cavity was higher, but at 1.15 μm it was lower. The measured reflectance of the Parsons cavity was appreciably higher than that computed from the measured reflectance of the lacquer and the geometry of the cavity, assuming the coating to be a perfectly diffuse reflector. Retro-reflectance measurements revealed that both lacquers reflected more radiant energy back into directions near the direction of incidence than would a perfect diffuser of the same directional-hemispherical reflectance, but the Parsons lacquer was by far the more pronounced retro-reflector. The principal conclusion is that the diffuse assumption can lead to significant errors in computing the absorptance of cavity-type receivers, when the cavity coating is in fact not diffuse.

Key words: Absorptance; black coatings; cavity absorptance;

cavity reflectance; laser-source reflectometer; Parsons black; retro-reflectance.

1. INTRODUCTION

Within the last ten years, Gillham [1], Kendall and Berdahl [2] and Willson [3] have each used absolute radiometers with cavity type receivors to realize a scale of irradiance based on electrical quantities. Each of these investigators has calculated the absorptance of his cavity receiver from the absorptance of the "black" lacquer with which the interior of the cavity was coated, under the assumption that the lacquer reflects in a perfectly diffuse manner. Since the only justification for this assumption is the matte appearance and low specular reflectance [4] of the lacquer, it is impossible to obtain an uncertainty or error limit for cavity absorptances obtained in this manner.

Willson [5,6] has estimated that the uncertainty in absorptance is reduced from ±2% for a flat receiver to ±0.3% for the cavity receiver which he describes, by the geometry of the cavity. But this estimate is also based on the assumption that the coating of the cavity reflects in a perfectly diffuse manner. As a counter example, consider a cavity coated with a perfect retro-reflector*. In this case there will be no "cavity

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*A perfect retro-reflector is a sample for which all of the flux which is not absorbed is reflected back along the path of the incident rays. A perfect mirror is a perfect retro-reflector for a normally incident ray. A retro-reflector is a sample for which more flux is reflected into a solid angle about the direction of incidence than would be reflected into this solid angle by a perfect diffuser of the same directional-hemispherical reflectance.

enhancement" of the absorptance, because all of the flux which is reflected off of the interior surface of the cavity will be lost out the hole in the cavity through which the incident flux entered. The cavity receiver will have the same absorptance and the same uncertainty in absorptance as a flat receiver coated with the same material.

The point is that if nothing quantitative is known about the geometric distribution of the flux reflected from the interior surfaces of the cavity, nothing quantitative can be said about the increase in the absorptance of the cavity over that of its interior surfaces. Consequently, nothing quantitative can be said about the decrease in the uncertainty of the absorptance of the cavity from that of its interior surfaces. This is very significant. After all, the principal reason for using a cavity type receiver on an absolute radiometer is to decrease the uncertainty in the absorptance of the receiver in order to decrease the uncertainty in the scale of irradiance which is realized by the radiometer.

In addition to the geometrical distribution of reflected flux there is another important source of uncertainty in the absorptance of the cavity receivers of Gillham, Kendall and Willson. This is the uncertainty in the absorptance of the black lacquer with which the cavities were coated. It arises from two sources. The first of these is the error inherent in the reflectance measurements from which the absorptance is calculated. Such measurements are subject to systematic errors which have not been well characterized. Thus it is impossible to estimate limits of error for such measurements with great confidence; unless these limits are left quite large. The second source of uncertainty is the

assumption that the reflectance of the lacquer coating on the interior of any given cavity is the same as has been reported in the literature for that particular lacquer. The effect of variations in painting technique on the reflectance of these lacquers has not been investigated so the samples on which the published reflectance measurements were made might not be at all representative of the coating of the cavity.

Kendall and Berdahl [2] have calculated the reflectance of the cavity receiver of the Primary Cavity radiometer which they describe to be 0.1%. However, in order to better determine the reflectance of this type of receiver, Kendall coated twenty flat samples and two cavities with black lacquers. On these samples we made directional-hemispherical reflectance measurements at two wavelengths, and retro-reflectance measurements with broad band radiation from a tungsten strip lamp. The purpose of this paper is to report the results of these measurements and to examine the suitibility of these lacquers for coating cavities in light of these results. The next three sections of this report will describe the samples, the directional-hemispherical reflectance measurements, and the retro-reflectance measurements, respectively. The results will be discussed in the concluding section.

2. DESCRIPTION OF THE SAMPLES

Twenty flat aluminum disks, 1.0 cm. in diameter by 0.2 cm. thick, were machined and marked with different letters to distinguish them. Ten of these disks were sprayed with the Thos. Parsons and Sons Optical

Black Lacquer* undercoat. They were then sprayed with the Thos. Parsons and Sons Optical Black Lacquer top coat until it appeared (to the unaided eye) that continued spraying was not increasing the absorptance of the coating. To see if this was true, five of the samples were then sprayed with more of the top coat. The same procedure was followed in the case of the remaining ten aluminum disks, except that the Eppley-Parsons Optical Black Lacquer under and top coats were used. Table 1 summarizes the preparation of the flat samples.

When the four groups of samples were viewed together, the samples coated with the Eppley-Parsons lacquer seemed to have a less matte appearance and a higher reflectance than the samples coated with the Thos. Parsons and Sons lacquer. It is not known whether this was due to a difference in the composition of the two lacquers, or a difference in the techniques with which they are applied. The two lacquers are supposed to be identical in composition, but the possibility of an improperly prepared batch or of an unknown difference in composition cannot be ruled out. The possibility that the Eppley-Parsons top coat was not mixed well enough before application cannot be ruled out either.

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*It is the policy of the National Bureau of Standards to avoid mentioning trade names in publications whenever possible. However, in this case it is necessary to use trade names in order to properly identify the materials of this investigation. These materials are of more than passing interest since they are recommended by the World Meteorological Organization for the coating of detectors employed in the measurement of solar and terrestrial thermal radiation.

Completely characterizing the properties of these lacquers as a function of the multitude of variables associated with spray painting techniques is far beyond the scope of this investigation.

Two cavities of the same dimensions as the cavity receivers in the Primary Cavity radiometers described by Kendall and Berdahl [2] were constructed. One was painted using a camels hair brush with the Thos. Parsons and Sons Optical Black Lacquer under and top coats, while the other was painted in the same way with the Eppley-Parsons Optical Black Lacquer under and top coats. The Thos. Parsons and Sons Lacquer used in this investigation was from the same batch and applied using the same techniques as that which was used to coat the receivers of the Primary Cavity Radiometers.

3. THE DIRECTIONAL-HEMISPHERICAL REFLECTANCE MEASUREMENTS

3.1 The Experimental Apparatus

A laser source, integrating sphere reflectometer, which has been described previously [7], was used to obtain the directional-hemispherical reflectance of the flat samples and the cavities at .6328 μm and 1.15 μm. This instrument has several noteworthy features. The integrating sphere itself is 35 cm in diameter. This large size minimizes the errors caused by the entrance, sample, and detector ports disturbing the geometry of the sphere. A He-Ne laser is the source of radiant flux for this instrument, and by changing the mirrors at the ends of the laser tube, radiation wavelengths of .6328 μm, 1.15 μm, or 3.39 μm may be selected. As might be expected, the radiant output of the laser is quite unstable. However, a second detector, a second amplifier, a mirror chopper, and a ratio multiplexer adequately compensate for this

instablility, and high precision results are obtainable.

Reference 7 presents a theoretical analysis of the instrument which indicated that it should be capable of producing reflectance data which are free from systematic error to within 1% of the measured reflectance values. This reference also describes an experimental verification of this analysis for high reflectance, specular samples. However, no experimental checks on the accuracy of the instrument in the low reflectance range were performed. In fact, this instrument had never been used to measure reflectances lower than 10% until the present work was begun. Consequently, tests for systematic errors at low reflectances levels were undertaken.

3.2 Tests of the Apparatus

Two tests for systematic error at low reflectance levels were conducted. The first test verified that the detector-amplifier system was linear in response. The second test determined that about 1% of the power in the incident beam missed the sample entirely and was incident instead on the highly reflective interior walls of the sphere. Obviously, this is a very serious source of systematic error at low reflectance levels. It turned out that the magnitude of this effect was variable, depending perhaps upon the mode structure of the laser, and it was necessary to measure the effect at set intervals during the directional-hemispherical reflectance measurements. Consequently, this test will be described in conjunction with the reflectance measurements in the next section.

In order to verify that the detector-amplifier system was linear in its response, the transmittance of a neutral density filter was first

measured using a recently calibrated optical pyrometer. Then the transmittance of the filter was measured with the integrating sphere reflectometer and its associated detector amplifier system. Anv cummulative non-linearity in the response of the detector amplifier system would manifest itself as a difference between the transmittance values obtained using the two different techniques.

In calibrating the transmittance of the neutral density filter, the filament of a strip lamp was viewed through an optical pyrometer. Brightness matches with the filament of the lamp were made when it was viewed through the filter and when it was viewed directly. Thus the radiance transmitted by the filter was equal to the black-body radiance at the mean effective wavelength of the pyrometer defined by the brightness temperature of the filament when viewed through the filter. Likewise, the radiance incident on the filter was equal to the blackbody radiance at the mean effective wavelength defined by the brightness temperature of the filament when viewed directly. The transmittance of the filter was calculated as the ratio of the transmitted radiance to the incident radiance. Data supplied by the manufacturer of the filter indicated that its transmittance at 7000 Å was about 1.03 times as high as its transmittance at 6000 Å. Thus, the mean effective wavelength of the pyrometer was not modified significantly by the filter, and it was assumed to be 6550 Å in both cases.

Three determinations of the transmittance of the filter were made using an optical pyrometer in the manner described above. The average value of the three determinations was 1.40%. The estimated limit of systematic error in this average is ±0.03%. It arises from the

uncertainty in the calibration of the pyrometer and the scatter in the brightness matches made with the pyrometer.

In order to measure the tranmittance of the neutral density filter with the integrating sphere reflectometer, the response of the detector-amplifier system to .6328 μm radiation was recorded both with the filter attenuating the laser beam between the chopper and the sphere, and with it removed. A zero level signal was also recorded when the laser beam was blocked off near the end of the laser, to correct for any zero off-set in the apparatus. The zero level signal was subtracted from both the signal obtained when the beam is attenuated by the filter and the signal obtained with the beam unattenuated. The ratio of the resulting zero corrected signals was taken as the transmittance of the filter as measured with the integrating sphere reflectometer.

Six separate determinations of the transmittance of the filter were obtained in this manner. The average of the six determinations was 1.40%. The maximum deviation of a single determination from the average, the estimated standard deviation of a single determination, and the estimated standard deviation of the mean were 0.17%, 0.09%, and 0.04%, respectively.

Thus the detector-amplifier system is probably linear in response to within a few percent from the highest flux level encountered in the directional-hemispherical reflectance measurements down to flux levels at least as low as one seventieth of this value. It is reasonable to assume that any cummulative non-linearities in the detector-amplifier system response will be largest for large fluxes and large electric signals, so no further linearity tests were made at lower flux levels.

3.3 Experimental Procedures and Results

In this section the directional-hemispherical reflectance measurements, which were made on the flat samples and the cavities, will be described.

The fraction of the incident beam that missed the sample and was incident on the sphere wall was evaluated as follows. A high-quality mirror was placed about 3 cm outside the sample aperture in the sphere, in a position to direct the laser beam to a room-temperature blackbody cavity lined with black velvet, that was located about 60 cm from the sample aperture. Three measurements were required in the form of an amplifier output in terms of a potential, which was read on a digital voltmeter. These were (1) when the laser beam was blocked between the chopper and the entrance aperture to the sphere (the zero reading, V_o), (2) when the laser beam was incident on the sphere wall (the 100% reading, V_{100}) and (3) when the laser beam passed out the sample aperture in the sphere (the scattered radiant energy reading, V_{sc}). The scattering correction factor, S, was computed as

$$S = \frac{V_{sc} - V_o}{V_{100} - V_o} \tag{1}$$

The directional-hemispherical reflectance of a sample also required three measurements, in the form of an amplifier output, which was read on the same digital voltmeter. These were V_o and V_{100} as above, and the sample measurement, V_s, obtained when the laser beam was incident on the sample near its center. The reflectance of the sample, $\rho(12°;2\pi)$ was then computed as

$$\rho(12°;2\pi) = \frac{(V_s - V_0) - (V_{100} - V_0)\, S}{(V_{100} - V_0) - (V_{100} - V_0)\, S} \quad (2)$$

Ten consecutive readings of the digital voltmeter, taken at uniform time intervals of approximately six seconds, were added to obtain each of the instrument values referred to above. Six replicate reflectance determinations were made on each sample. The mean and the estimated standard deviation of a single one of the six replicate reflectance determinations are reported in Tables 2 and 3. In the instances where two values of reflectance are reported for a single sample at a single wavelength, they are the results of measurements taken about six months apart. The cavity reflectance measurements were taken at various times during the six month interval. The differences in reflectance obtained on the same sample at different times during the six month period are in many cases larger than can be accounted for by the observed statistical scatter. The observed differences may be real, and is perhaps related to some factor such as humidity of the laboratory atmosphere. On the other hand, it may be due to some systematic error in the measurement process that has not been identified and corrected for. It was noted that the scattering error is variable, and that it does not drift slowly with time, but changes abruptly by comparatively large amounts. An unrecognized change in the scattering error might be responsible for the observed differences. In any case, the results of these measurements are still significant for the purpose of this paper.

Gillham [8] has published a curve for the spectral reflectivity of samples of optical black lacquer manufactured by Thos. Parsons Ltd. He obtained a reflectance of approximately .010 at .63 μm and .016 at 1.15 μm,

with an estimated accuracy of ±.0025. Whether the differences between his values and the values reported in this paper are due to differences in the formula for the lacquers, or to experimental errors in either or both sets of data, or to some other cause is not known.

For a Primary Cavity Radiometer cavity coated with a perfect diffuser, Kendall has prepared a graph of cavity absorptance as a function of coating absorptance. In terms of reflectances, his graph shows that for coating reflectances below 3%,

$$\rho_c \simeq 0.07\ \rho \qquad (3)$$

where ρ and ρ_c are the coating and cavity directional-hemispherical reflectances, respectively. It is of interest to compare the minimum and maximum measured values of the directional-hemispherical reflectance of the cavities with the values calculated using Eq. 3 from the measured directional hemispherical reflectance of the flat samples. This is done in Table 4. Each pair of entries in a box labeled "measured" consists of the smallest and largest cavity reflectance values reported in Table 3 for a given type of lacquer at a given wavelength. Each pair of entries in a box labeled "calculated" consists of values calculated using Eq. 3 from the smallest and largest flat sample reflectance values reported in Table 2 for a given type of lacquer at a given wavelength. The poor agreement between the measured and calculated values for the Thos. Parsons lacquer could arise from any of three sources. The directional - hemispherical reflectance measurements might be in error; the lacquer as applied to the flat samples might not be representative of the lacquer as applied to the interior of the cavity; or the distribution of reflected flux from the lacquer might deviate significantly from that of a perfect diffuser. Having attempted

to eliminate the first possibility, the retro-reflectance measurements described in the next section were undertaken to investigate the last two possibilities.

4. THE RETRO-REFLECTANCE MEASUREMENTS

4.1 Description of the Apparatus

Figure 1 is a schematic diagram of the apparatus which was used to make the retro-reflectance measurements. The image of the filament of a tungsten strip lamp was focused by a lens through a baffle onto a small aperture in an opaque screen. The chopper for a synchronous amplifier was so located that it chopped the beam from the lamp between the lens and the baffle. The lamp, lens, chopper and baffle were all enclosed in a box which was light tight except for one opening; the aperture on which the image of the filament was focused. Through this aperture the portion of the chopped beam from the lamp, which passed through the baffle, emerged from the box. An image of the aperture was focused through the opening in the box onto the sample to be measured after reflection off a beam splitter, as shown in the figure. The portion of the incident beam which was transmitted through the beam splitter was collected on a high absorptance surface located a considerable distance from the detector and out of its field of view. The flux reflected off the sample into a cone centered about the incident beam was collected, after transmission through the beam splitter, by a large spherical mirror and focused onto a thermopile detector whose receiver was 3 mm on a side. The solid angle subtended by the incident beam at the sample was approximately 0.001 π steradians, and the solid angle over which the retro-reflected flux was collected was 0.0144 π steradians. The estimated

limits of systematic error in the solid angle over which the flux was collected is ±2%.

The sample holder had two rotational degrees of freedom which allowed the sample to be rotated about both horizontal and vertical axes passing through the geometrical center of the front surface of the sample. For the remainder of this paper, the retro-reflectance of a sample will be defined as the ratio of the flux reflected by the sample into a conical solid angle of $0.0144\ \pi$ to the flux incident on the sample, where the incident flux is confined to a solid angle of $0.001\ \pi$ symetrically located within the solid angle of collection. Thus the directions of incidence and reflectance are identical, and the retro-reflectance is a function of only one direction in space.

The spectral composition of the flux used in the retro-reflectance measurements is given by the product at each wavelength of the radiance of the filament of the lamp, the transmittances of the lamp envelope and the lens, the reflectance of the three aluminum coated mirrors, the atmospheric transmittance of the optical path, the reflectance and transmittance of the beam splitter, and the responsivity of the detector. The lamp had a tungsten ribbon filament and a lime glass envelope. The lens was quartz. The spectral radiance of the filament was computed from the measured brightness temperature of the lamp (2300 K) using the emissivity data of DeVos [9] and the envelope transmittance. The envelope

transmittance as well as the transmittance of the lens were taken from the AIP Handbook [10], and the spectral reflectance of the aluminum mirrors was taken from the data of Bennett, et al., [11] and Twidle [12]. The spectral transmittance of the atmosphere over the approximately 500cm path length was taken from the data of Wyatt, Stull and Plass [13] for 0.005 precipitable cm of water vapor (50% relative humidity at 72°F). The relative spectral responsivity of the detector was measured between 0.4 μm and 1.8 μm by a modification of a technique which has been described previously [14]. It was found to be uniform to within ±5% in this spectral region. The spectral transmittance and reflectance of the beam splitter were measured on commercial double beam spectrometers over the spectral range from 0.4 μm to 3.0 μm. The approximate spectral composition of the flux as calculated from the above described data is shown in Fig. 2.

A number of tests were performed on the apparatus to determine the accuracy with which the retro-reflectance measurements could be made. They are described in the next section.

4.2 Tests of the Apparatus

In order to verify that the detector amplifier system which was used in these measurements was linear in response, the transmittance of the neutral density filter whose calibration was described in Section 3.2 was measured. Again the .6328 μm radiation from the laser was used. The response of the detector-amplifier system, which was used in the retro-reflectance measurements, was recorded with the beam directly incident on the detector; and when the beam was attenuated by the filter. A zero-level signal was also recorded. The transmittance was calculated

from this data in the same manner as described in Section 3.2 in reference to the transmittance measurements made with the integrating sphere reflectometer and its detector-amplifier system. It was necessary to use the laser as a source in order to achieve the highest flux level which was experienced in the retro-reflectance measurements, while at the same time restricting the flux to the wavelength region which was effective in the calibration of the transmittance of the filter using the optical pyrometer.

The average of six measurements of the transmittance of the filter by this technique is 1.44%. The maximum deviation of a single measurement from the average, the estimated standard deviation of a single measurement, and the estimated standard deviation of the mean are 0.06%, 0.03%, and 0.01%, respectively.

This result requires that a correction factor of 0.97 be applied to those values of retro-reflectance which are measured to be 1.44% with this apparatus. The uncertainties associated with this correction factor are an estimated limit of systematic error of ±0.02 arising from the uncertainty in the measurement of the transmittance of the filter with the optical pyrometer which was described earlier, and a three standard deviation uncertainty of ±0.02 arising from the random errors in the measurement of the transmittance of the filter with the detector amplifier system used for the retro-reflectance measurements. The measured retro-reflectance values reported in this paper for all of the materials except the black electrical tape fall between 0.02% and 1.6%. It is reasonable to assume that any cummulative non-linearity in response of the detector amplifier system will be largest for large fluxes and

large electrical signals. Thus, it is very likely that the errors from non-linearity arising between 0.02% and 1.6% retro-reflectance are less than those arising between 1.6% and 100% retro-reflectance. Since no other data on the linearity of response of the apparatus between 0.02% and 1.6% retro reflectance were available, it was subjectively decided to apply a correction factor to 0.96 to all of the measured retro-reflectance values reported in this paper. It is estimated that the limit of error associated with this correction factor is ±0.06 for retro-reflectance values between 0.02% and 1.6%.

Ideally, the responsivity of the apparatus should be constant for all directions of reflection from the samples which are collected by the spherical mirror (11) in Figure 1, and zero for all other directions of reflection. In order to investigate the actual responsivity of the apparatus as a function of the direction of reflection from the sample, a gold mirror was mounted in the sample holder. It was rotated about the horizontal and vertical axes passing through the geometric center of its front surface, and the output voltage of the detector was measured as a function of the direction of the reflected beam. Since the incident beam subtended a much smaller solid angle than that over which the retro-reflected flux was collected, it was possible, using this technique, to measure the responsivity of the apparatus for various portions of the solid angle of collection. This was done by directing the beam reflected from the gold mirror onto five different portions of the spherical mirror (11) as shown in Figure 3. The average responsivity over the surface of the mirror was approximated by the average of the five measured values. The ratio of the average responsivity over the surface of the mirror to

that of its central portion is 1.021. Thus a correction factor of 0.98 was applied to all of the measured retro-reflectance values reported in this paper. The estimated limit of systematic error associated with this correction factor is ±0.02 for all of the materials except the black electrical tape for which it is ±0.04.

The rest of the spherical solid angle centered on the sample* was investigated in a manner similar to that used to investigate the solid angle over which the retro-reflected flux was collected. However, the emphasis here was on directing the beam onto other portions of the apparatus which might scatter light into the field of view of the detector after only one or two reflections.

For the most part, the amount of flux getting to the detector when the beam was directed anywhere except in the vicinity of the beam splitter was so small that it could not be detected. A few directions were located in which measureable signals were produced. In each of these cases judicious placement of highly absorbing cloth and baffles was sufficient to reduce these signals to the point that they could not be detected. When the beam was directed into the immediate vicinity of the beam splitter, non-negligible signals were recorded. It is not known whether these were due to scattering at the surface of the gold mirror, or scattering by portions of the beam splitter that were not being used, or some other source. Due to this difficulty and to the rather poor

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*That is, all of the spherical solid angle whose center is the sample except for the solid angle over which the flux was collected.

angular resolution all that could be determined was that the correction for this effect could not be less than 0% nor larger than 6%. So a correction factor of 97% with an estimated limit of systematic error in the correction of ±3% was employed.

All of the retro-reflectances described in this paper were measured relative to the reflectance of a gold mirror. The data of Bennett and Ashley [15] were used to calculate a reflectance of 0.965 for such a mirror for the flux distribution shown in Figure 2. Thus a correction factor of 1.036 was applied to all of the measured retro-reflectance values to allow them to be reported on an absolute scale. The estimated limit of uncertainty of this correction factor, ±0.03, reflects both the uncertainties in the spectral flux distribution and in the spectral reflectance of the mirror.

All of the correction factors and the estimated limits of uncertainty associated with them are summarized in Table 5. The product of all of these correction factors is 0.945. The sum of the absolute values of the estimated limits of certainty is 0.14 and the square root of the sum of the squares of the estimated limits of uncertainty is 0.08. Two comments about the significance of these cummulative estimated limits of uncertainty are necessary. First, this uncertainty is associated with the absolute error, that is, with the deviation of a reported value from the true value on an absolute scale of reflectance. Notice that an error in the reflectance of the gold mirror contributes the same percentage error to all of the retro-reflectance values. Thus the ratio of the reported retro-reflectance values of any two samples has no uncertainty arising from this source of error. Likewise, all of the sources of error listed

in Table 5, contribute larger errors to the individual retro-reflectance values of the different samples than they contribute to the ratios of these retro-reflectance values. Thus the limit of uncertainty associated with the relative errors in the reported values is smaller than that associated with the absolute error in them. This limit of uncertainty is estimated to ±5% of the reported value. Finally, these limits of error do not reflect the uncertainty in the measurement of the solid angle (estimated limit of uncertainty of ±2% of the solid angle), nor do they reflect the uncertainty in the actual shape of the spectral distribution of flux used in these measurements, except in its effect on the uncertainty in the reflectance of the gold mirror for this flux distribution.

4.3 Experimental Procedures and Results

The sample holder had a flat surface against which the rear surface of each sample was pressed when mounted in the holder. Thus the orientation of the normal to the front surface of a sample relative to the holder was the same for all of the samples, except for small deviations introduced by any lack of parallelism of the front and rear surfaces of the sample. This fact was used to align the samples for the retro-reflectance measurements. The experimental procedure was as follows.

A first-surface gold mirror of the same dimensions as the flat samples coated with Parsons black lacquer was mounted in the sample holder. The holder was then aligned so that the beam reflected off the mirror was incident on the central portion of the spherical mirror (11) shown in Figure 1. When the room lights were turned off, the location of this beam on the mirror could be observed visually due to the

scattering from dust particles on the mirror's surface. Hence, the normal to the surface of the gold mirror could be made to pass through the approximate center of the spherical mirror. When properly aligned in this manner the voltage output from the detector was recorded. After the completion of this step the gold mirror was removed from the sample holder and replaced by one of the samples of this investigation. Thus this sample was aligned so that its normal passed through the approximate center of the spherical mirror. This position of the sample holder was taken as 0° of rotation about the vertical axis through the front surface of the sample. The voltage output of the detector was then recorded for the following rotations about the vertical axis: 0°, -25°, -15°, -5°, 5°, 0°, 15°, 25°, 35°, 45°, 0°, 55°, 65°, 75°, 0°. The repeated readings taken at 0° were to check for instrument drifts during the measurement.

After each set of retro-reflectance measurements the gold mirror was again placed in the sample holder, the alignment checked visually, and the voltage output from the detector recorded.

The $BaSO_4$ was the first sample to be measured, then samples E, C, J, N, and L in that order, and finally the black electrical tape. The results are shown in Table 6 and Figure 4. Since the solid angle of collection was 0.0144 π, the retro-reflectance of a perfect diffuser whose directional-hemispherical reflectance was 100%, would be given by 0.0144 cos θ, where θ is the angle between the direction of incidence (equals direction of exitence) and the normal to the perfect diffuser. The retro-reflectance of the $BaSO_4$ sample was measured to be in excess of 0.015 for small θ. This is approximately 5% higher than the retro-reflectance of a 100% reflectance perfect diffuser, but this difference

is relatively small compared to the ±14% limit of uncertainty which must be associated with the measurements on an absolute scale of reflectance. However, the $BaSO_4$ does not have a 100% directional-hemispherical reflectance over the entire wavelength range of the flux distribution shown in Figure 2, so the measured difference probably is significant. The unbroken line in Figure 4 is a plot of 0.01504 cos θ for comparison with the measured curve for $BaSO_4$. Since the ordinate in the figure is linear with the log of the retro-reflectance, the cosine curve can be displaced downward for comparison with any of the other curves. It is interesting to notice that sample E, whose directional-hemispherical reflectance is approximately 1.5%, has the same retro-reflectance at normal incidence as a perfect diffuser whose reflectance is 4%, and at 55° as a perfect diffuser whose reflectance is 6%. Also notice that a low reflectance specularly reflecting material such as the black electrical tape would be a better choice for coating the interior of a cavity receiver than either type of Parsons Optical Black Lacquer, as long as the normal to the bottom of the cavity were directed more than about 10° away from the opening of the cavity.

5. CONCLUSION

Since the mean wavelength of the flux distribution of the retro-reflectance measurements is close to 1.15 μm, it is of some interest to compare the measured values of the directional-hemispherical reflectance of the PACRAD cavities at 1.15 μm with values calculated from the broad band retro-reflectance values of the flat samples coated with the same lacquer. This is done in Table 7. Each pair of entries in a box labeled "calculated" consists of cavity reflectance values

calculated* from the smallest and largest flat sample retro-reflectance values reported in Table 6 for a given type of lacquer at an angle of incidence of 55°. In Table 4 a similar comparison was made between the measured valued of the directional-hemispherical reflectance of the PACRAD cavities and the values calculated from the results of the directional-hemispherical reflectance measurements on the flat samples. The data in both of these tables is summarized qualitatively in Table 8.

It seems unlikely that the inconsistencies in this table are due to experimental errors in the reflectance measurements, since either the directional-hemispherical or the retro-reflectance appartus would have to measure too low for some of the samples and too high for others, and a large amount of effort was expended looking for such effects. It seems much more likely that the reflectance characteristics of the same type of lacquer were different depending upon whether the coating was applied to a flat sample or to a cavity. This conclusion is further supported by the fact that the lacquers were sprayed onto the flat samples but were brushed onto the cavities.

Other more significant conclusions can also be drawn from the data in this paper. First, it appears that there can be considerable variation in the reflectance of samples of either of the two types of black lacquers studied even when the samples are prepared at the same time

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*In this case the values were calculated by multiplying the flat sample retro-reflectance values by 9.7, the ratio of the solid angle from the base of the PACRAD cavity to the opening, to the solid angle of collection used in the retro-reflectance measurements.

according to the directions specified by the manufacturer. Thus in order to determine the reflectance or absorptance of an object coated with either of these lacquers, measurements must be made upon that object. Confidence cannot be put in values taken from the literature, nor even in measurement taken on different samples of the lacquer prepared at the same time as the object was coated. Secondly, in order to achieve high absorptance, cavity recievers should have bottoms whose normals are directed well away from the opening of the cavity and they should be coated with a specular black material, even if its directional-hemispherical reflectance is higher than that of the available "matte" coatings.

6. REFERENCES

1. Gillham, E. J., Proc. Roy. Soc. London, Ser. A <u>269</u>, 249 (1962).
2. Kendall, J. M., and Berdahl, C. M., Appl. Opt. <u>9</u>, 1082 (1970).
3. Willson, R. C., <u>Experimental and Theoretical Comparisons of the JPL Active Cavity Radiometric Scale and the International Pyrheliometric Scale</u>, (TR 32-1365, Jet Propulsion Laboratory, Pasadena, Calif. Feb. (1969).
4. <u>Eppley-Parsons Optical Black Lacquer</u>, Advertising Brochure, Eppley Laboratory, Inc., Newport, R.I.
5. Willson, R. C., <u>Experimental and Theoretical Comparisons of the JPL Active Cavity Radiometric Scale and the International Pyrheliometric Scale</u>, (TR 32-1365, Jet Propulsion Laboratory, Pasadena, Calif. Feb. (1969), p. 14.
6. Willson, R. C., private communication.
7. Kneissl, G. J., and Richmond, J. C., <u>A Laser-Source Integrating Sphere Reflectometer</u>, Nat. Bur. Stand. (U.S.), Tech. Note 439, 69 pages (February 1968).
8. Gillham, E. J., Brit. J. Appl. Phys., <u>4</u>, 151 (1953).
9. Devos, J. C., Physica, <u>20</u>, 690 (1954).
10. Gray, D. E., Ed., <u>American Institute of Physics; Handbook</u> (McGraw-Hill Book C., New York, 1963), 2nd ed., Chap. 6, p. 58.
11. Bennett, H. E., Bennett, J. M., and Ashley, E. J., J.O.S.A. <u>52</u>, 1247 (1962).
12. Twidle, G. G., Brit. J. Appl. Phys. <u>8</u>, 338, (1957).
13. Wyatt, P. J., Stull, V. R., and Plass, G. N., Appl. Opt. <u>3</u>, 238 (1964).

14. Goebel, D. G., Poole, E. W., and Hartsock, R. G., Appl. Opt. 8, 1749 (1969).

15. Bennett, J. M., and Ashley, E. J., Appl. Opt. 4, 221 (1965).

TABLE 1

Coating	Thos. Parsons and Sons Under Coat and Top Coat		Eppley-Parsons Under Coat and Top Coat	
Samples	A B C D E	F G H I J	K L M N O	P R S T U
Extra Top Coat	YES	NO	YES	NO

TABLE 2

Reflectance of Flat Samples

Sample	at 0.6328 μm		at 1.15 μm	
	ρ	S.D.	ρ	S.D.
A	0.0153	0.0005	----	----
B	.0132	.0003	0.0246	0.0002
C	.0142	.0004	.0242	.0004
	.0161	.0011	.0273	.0004
D	.0161	.0009	----	----
E	.0138	.0008	----	----
	.0160	.0016	.0279	.0005
F	.0187	.0011	----	----
G	.0216	.0013	.0328	.0004
H	.0213	.0011	.0374	.0002
I	.0191	.0005	----	----
J	.0171	.0008	----	----
	.0196	.0008	.0305	.0001
K	.0348	.0013	.0474	.0006
L	.0346	.0006	----	----
	.0375	.0012	.0512	.0002
M	.0340	.0012	.0448	.0004
N	.0331	.0009	----	----
	.0372	.0014	.0485	.0003
O	.0333	.0008	----	----
P	.0340	.0009	----	----
	.0359	.0013	----	----
R	.0341	.0008	----	----
S	.0342	.0009	----	----
T	.0357	.0005	----	----
U	.0380	.0007	----	----

TABLE 3

Reflectance of Blackbody Cavities

at 0.6328 μm		at 1.15 μm	
Thos. Parsons			
ρ	S.D.	ρ	S.D.
.00314	.00028	.00251	.00019
.00400	.00074	.00292	.00025
.00436	.00047	.00276	.00018
.00334	.00050		
.00352	.00056		
.00208	.00042		
Eppley-Parsons			
.00366	.00021	.00367	.00023
.00243	.00104	.00342	.00016
.00301	.00039	.00341	.00018
.00224	.00048		
.00247	.00019		
.00199	.00046		

TABLE 4

lacquer	Thos. Parsons		Eppley-Parsons	
wavelength	measured	calculated	measured	calculated
0.6328 µm	0.0021 0.0044	0.0009 0.0015	0.0020 0.0037	0.0023 0.0027
1.15 µm	0.0025 0.0029	0.0017 0.0026	0.0034 0.0037	0.0031 0.0036

Directional-Hemispherical Reflectances for PACRAD Cavities. Maximum and minimum measured values vs. values calculated from the maximum and minimum directional-hemispherical reflectance values measured for flat samples.

TABLE 5

Source of Error	Correction Factor	Estimated Limit of Uncertainty
non-linearity of system	0.96	0.06
variations in responsivity over solid angle of collection	0.98	0.02
responsivity to flux reflected into solid angles other than that of collection	0.97	0.03
reflectance of gold mirror	1.036	0.03

TABLE 6

Retro-reflectance of the samples for a
0.0144 π steradian solid angle of collection, in percent

Angle of Incidence	$BaSO_4$	C	E	J	L	N	Electric Tape
-25°	1.325	0.0545	0.0529	0.0539	0.0618	0.0648	0.00499
-15°	1.437	.0558	.0546	.0603	.0763	.0834	.0105
-5°	1.501	.0564	.0556	.0674	.0895	.1028	.1433
0°	1.504	.0571	.0562	.0699	.0913	.1081	2.222
5°	1.518	.0569	.0561	.0688	.0900	.1064	0.7111
15°	1.471	.0560	.0549	.0632	.0784	.0888	.0153
25°	1.381	.0549	.0540	.0576	.0632	.0687	.00506
35°	1.254	.0538	.0531	.0527	.0498	.0533	.00343
45°	1.094	.0528	.0511	.0497	.0404	.0434	.00242
55°	0.911	.0515	.0489	.0478	.0336	.0362	.00175
65°	0.711	.0497	.0463	.0467	.0296	.0327	.00194
75°	0.523	.0497	.0446	.0474	.0338	.0320	.00101

TABLE 7

Thos. Parsons		Eppley Parsons	
measured	calculated	measured	calculated
0.0025	0.0047	0.0034	0.0024
0.0029	0.0050	0.0037	0.0027

Directional-Hemispherical Reflectances at 1.15 μm for PACRAD cavities. Measured values vs. values calculated from broad band retro-reflectance values measured for flat samples.

TABLE 8

Type of data used in calculation		Type of Lacquer	
		Thos. Parsons	Eppley-Parsons
directional-hemispherical reflectance	0.6328 μm	much too low	about right
	1.15 μm	a little too low	about right
retro-reflectance		much too high	too low

A Qualitative Comparison of How Much Too Low or Too High the Calculated Directional-Hemispherical Reflectance Values Were Relative to the Measured Directional-Hemispherical Reflectance Values for PACRAD Cavities.

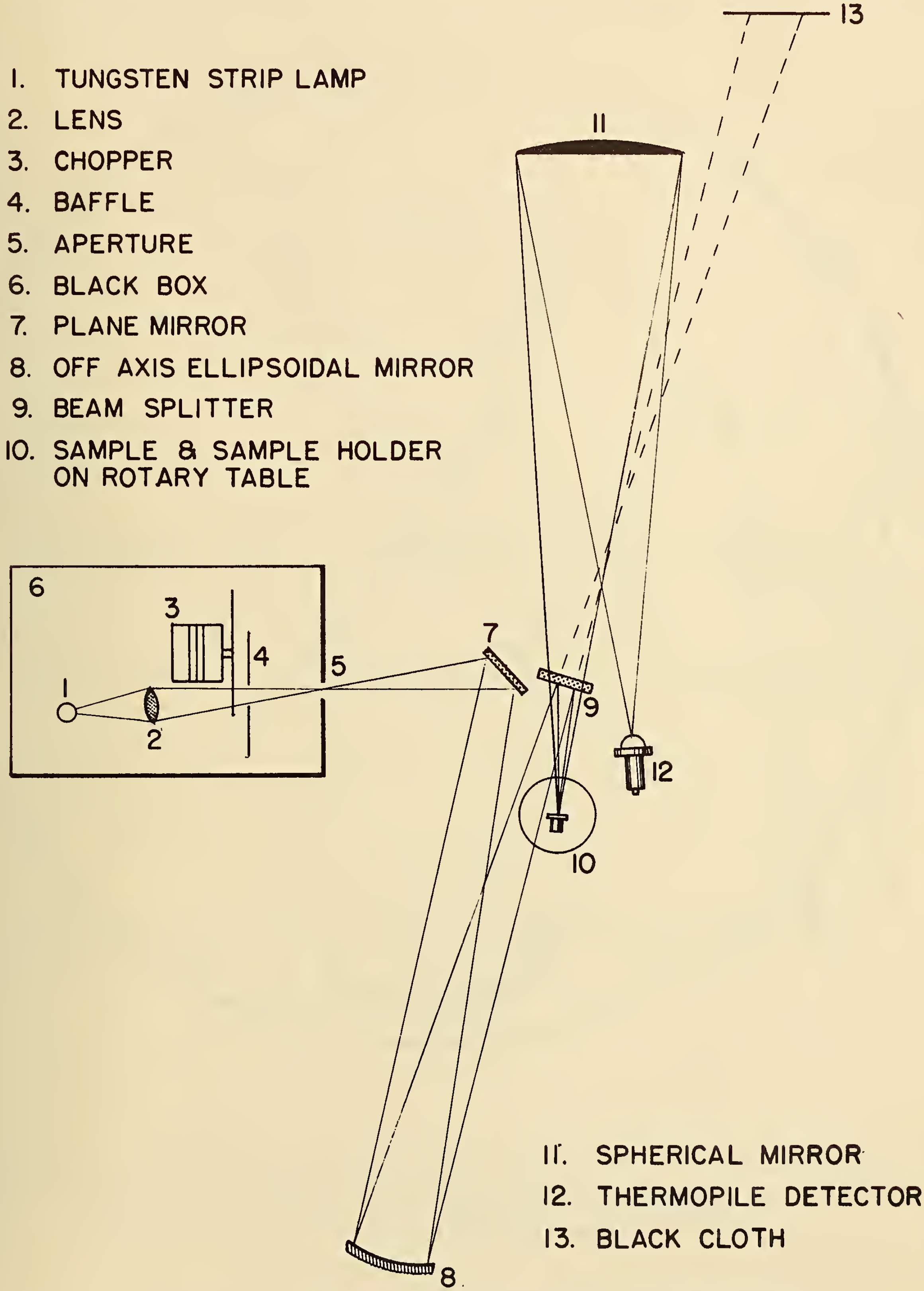

Fig. 1. Schematic diagram of the retro-reflectance apparatus.

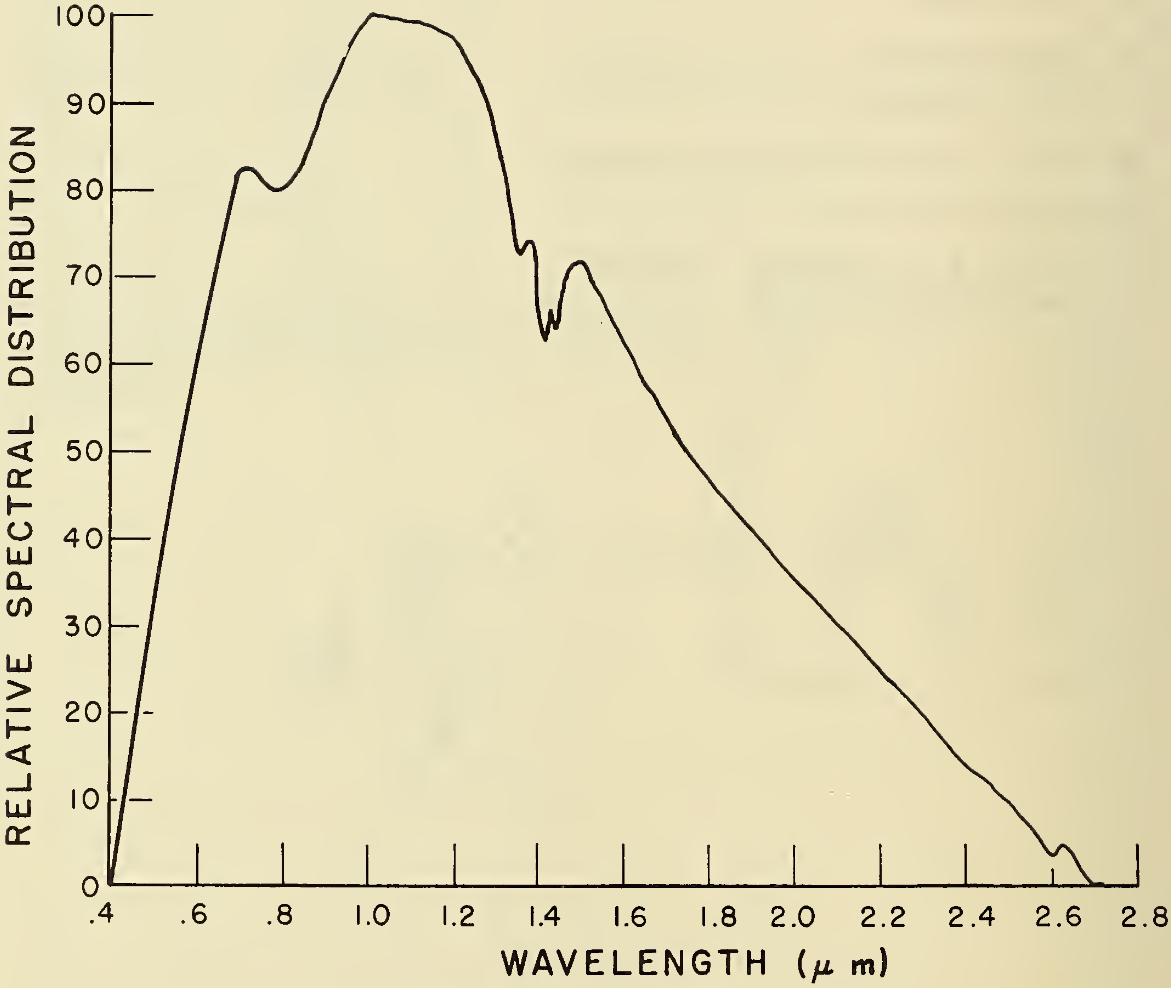

Fig. 2. The relative spectral distribution of the radiation used in the retro-reflectance measurements.

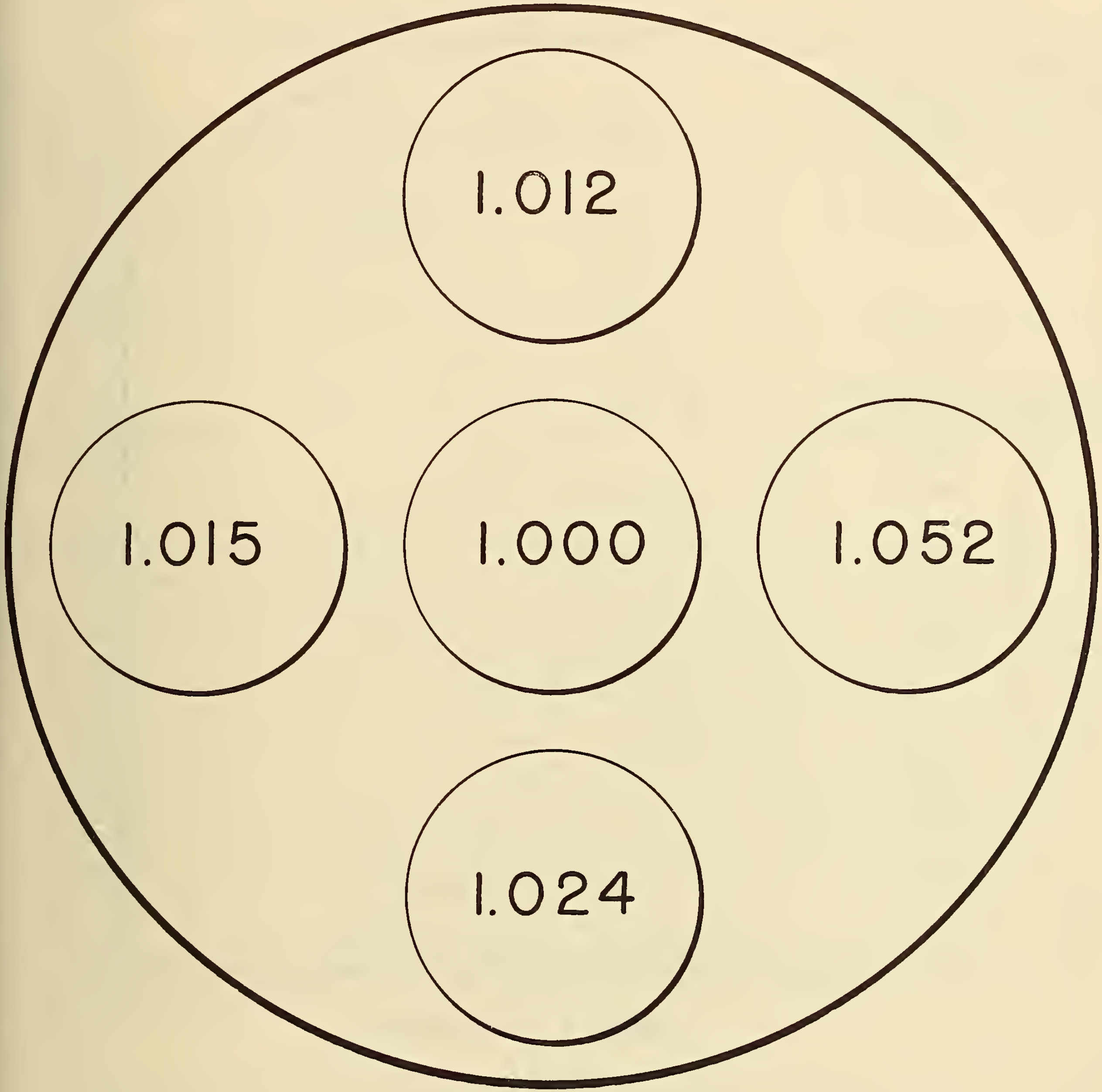

Fig. 3. The relative sensitivities of five portions of the solid angle over which the retro-reflected flux was collected.

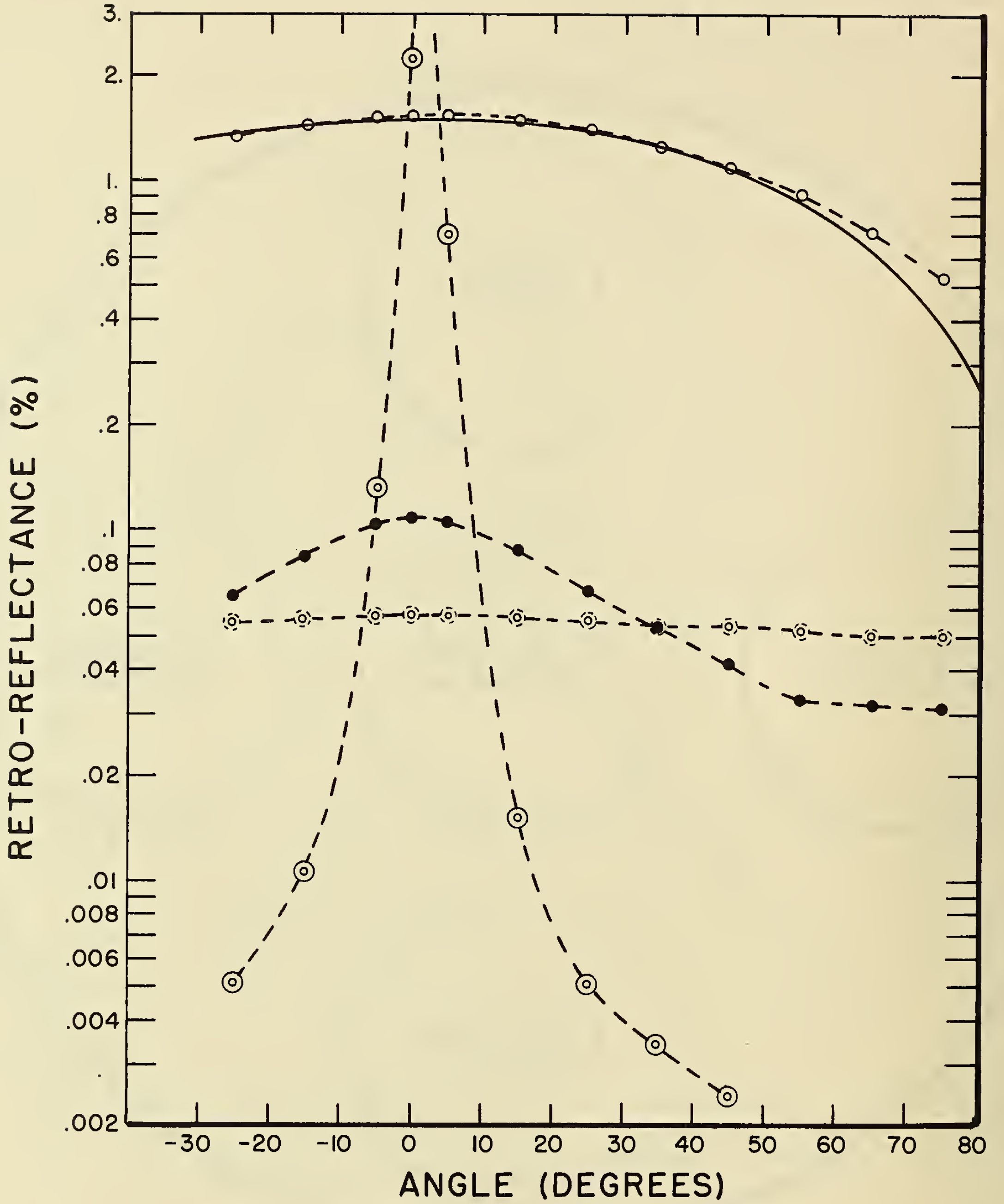

Fig. 4. The variation of retro-reflectance with angle of incidence for a perfect diffuser (——), $BaSO_4$ (o- - - -), samples E (◎- - - -), and N (●———), and black electrical type (◎- - - -). The retro-reflectances of samples C and L were very similar to those of E and N, respectively, and are not shown there.

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

The directional-hemispherical reflectance of a number of flat samples that had been coated with Parsons Optical Black Lacquer procured from Thos. Parsons and Sons and The Eppley Laboratory, respectively, was measured at 0.6328 and 1.15 μm with a laser-source integrating sphere reflectometer. The reflectance varied significantly with method of application, and was significantly higher for the Eppley lacquer than for the Parsons lacquer. The reflectance of two cavity receivers, one coated with each lacquer, was also measured. At 0.6328 μm the reflectance of the Parsons cavity was higher, but at 1.15 μm it was lower. The measured reflectance of the Parsons cavity was appreciably higher than that computed from the measured reflectance of the lacquer and the geometry of the cavity, assuming the coating to be a perfectly diffuse reflector. Retro-reflectance measurements revealed that both lacquers reflected more radiant energy back into directions near the direction of incidence than would a perfect diffuser of the same directional-hemispherical reflectance, but the Parsons lacquer was by far the more pronounced retro-reflector. The principal conclusion is that the diffuse assumption can lead to significant errors in computing the absorptance of cavity-type receivers, when the cavity coating is in fact not diffuse.

17. KEY WORDS (Alphabetical order, separated by semicolons) absorptance; black coatings; cavity absorptance; cavity reflectance; laser-source reflectometer; Parsons black; retro-reflectance.

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